INVESTIGATION OF THE EFFECTS OF PRECONDENSATION SECTIONS IN TWO-DIMENSIONAL SUPERSONIC FLOW

A THESIS

Presented to

Georgia School of Technology

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Aeronautical Engineering

by

William DeForest McCauley

May 1951

INVESTIGATION OF THE EFFECTS OF PRECONDENSATION SECTIONS IN TWO-DIMENSIONAL SUPERSONIC FLOW

Approved:

Date Approved by Chairman May 26, 1951

ACKNOWLEDGEMENTS

In fulfillment of this thesis, I wish to express my sincere appreciation to Professor H.W.S. LaVier for suggesting the thesis topic and for his invaluable assistance and guidance in its completion. I am also indebted to Professors R. G. Fleddermann and M. J. Goglia who, besides serving on the reading committee, also gave invaluable aid in problems encountered in the thesis. Acknowledgement must also be given to the experience and help of the shop personnel, and to the staff and secretarial personnel of the Daniel Guggenheim School of Aeronautics who supplied the equipment necessary for the completion of this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

p	Static pressure
C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
γ	Ratio of specific heats $(C_p/C_v = 1.4)$
M_{1N}	Normal Mach number
ρ	Density
T	Temperature
L	Latent heat of vaporization
W_V	Weight of water vapor
W_A	Weight of air
x	Specific humidity (W_V/W_A)
ν	Prandtl-Meyer angle
θ_o	Expansion angle actually used
θ_{MAX}	Maximum permissible expansion
R_e	Reynolds number
M	Mach number
A	Area

Subscripts

$*$	Conditions at throat
1	Conditions immediately ahead of shock
2	Conditions behind shock

INVESTIGATION OF THE EFFECTS OF PRECONDENSATION SECTIONS IN TWO-DIMENSIONAL SUPERSONIC FLOW

SUMMARY

For the purpose of testing the characteristics of a precondensation section, a supersonic nozzle and precondensation section were designed and constructed.

The supersonic nozzle was first tested alone, observing the schlieren and pressure and temperature measurements. Next, tests were conducted with the precondensation section added, the flow again being observed by schlieren and pressure and temperature measurements in the nozzle and precondensation section.

Results obtained showed that the precondensation section would induce condensation ahead of the test section as expected. For the conditions under which this experiment was run no oblique condensation shocks appeared in the nozzle test section. This was found to be true with or without utilizing the precondensation section. On days when the Relative Humidity was low oblique shocks with condensation could be induced in the test section by the utilization of the precondensation section when they would not otherwise be present.

INTRODUCTION

A preliminary study of condensation phenomena reveals that air-vapor mixtures will have condensation occurring soon after the saturation point has been passed, but in an air stream which is being rapidly expanded, expansion occurs so rapidly that the time factor involved does not give condensation a chance to occur and the air-vapor mixture goes on to a metastable supersaturated condition. The main factor which governs condensation in the supersaturated state is the formation of droplets beyond a certain critical radius (approximately 10^{-7} centimeters).[1] If the droplet is less than the critical radius, it will re-evaporate because it is not in equilibrium with respect to it. If the radius of the droplet is greater than the critical radius, it is in equilibrium with the vapor and will continue to grow by the addition of other water vapor molecules through collisions. Actually, condensation shock is the rapid formation of a large number of these droplets which causes a collapse of the supersaturated state.

---

[1] Joseph H. Keenan, Thermodynamics (New York: John Wiley and Company, Inc., 1946), p. 438.

With steam shocks the same type of phenomena occurs the main difference being that steam is a pure vapor and this problem concerns an air-vapor mixture. With steam shocks it is possible to construct what is called a Wilson[2] line on a Mollier chart. This line lies almost parallel to the saturation line, but somewhat below it, and determines points of supersaturation where condensation will occur.

Condensation shocks may be treated analytically in a manner similar to the treatment given oblique shocks. This is easily shown with the realization that condensation has the following additional consequences:

1) heat of vaporization is gained

2) loss of air mass due to condensation into droplets

3) change in ratio of specific heats.

The aforementioned information brings up three important questions:

1) At what Mach number does the supercooled vapor condense?

2) What mass of water is precipitated?

3) How much heat is supplied to the air?

---

[2] J. I. Yellot, "Supersaturated Steam," <u>American Society of Mechanical Engineers Transactions</u>, 56:411, June, 1934.

Since gas dynamics cannot answer this, they must be treated as independent variables.

Solutions for change of properties across a condensation shock have been obtained[3] and are as follows:

$$\frac{p_2}{p_1} = \frac{\gamma}{\gamma+1}\left(M_{IN}^2-1\right)\left[1 \pm \sqrt{1-Z}\right]+1$$

$$\frac{\rho_1}{\rho_2} = \frac{V_2}{V_1} = 1 - \frac{1}{\gamma+1}\left(\frac{M_{IN}^2-1}{M_{IN}^2}\right)\left[1 \pm \sqrt{1-Z}\right]$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}\frac{\rho_1}{\rho_2} = \frac{p_2}{p_1}\frac{V_2}{V_1}$$

$$M_2 = \left\{(1+Q)\left(\frac{1}{M_{IN}^2}+\frac{\gamma-1}{2}\right)\left(\frac{V_1}{V_2}\right)^2 - \frac{\gamma-1}{2}\right\}^{-\frac{1}{2}}$$

$$Z = \frac{M_{IN}^2}{(M_{IN}^2-1)^2}\left\{M_{IN}^2+\frac{2}{\gamma+1}\right\}(\gamma^2-1)\,Q$$

$$Q = \frac{L\,(x_1-x_2)}{C_p\,T_0}$$

---

[3] J. V. Charyk, "Condensation Phenomena in Supersonic Flow," (Unpublished Ph. D. Thesis, California Institute of Technology, Pasadena, 1946), p. 3-54.

If all the water condenses out x = 0 and properties downstream of shock may be solved directly; however, this does not occur and x_2 must be considered as saturated or possibly supersaturated, which requires a trial and error solution. This type of solution is tedious and involves variables which are difficult, if not impossible, to determine. Even after solution values obtained may not be reliable due to re-evaporation. It is therefore very desirable to eliminate the condensation shock.

The two methods employed in present practice are:[4]

1) Pre-drying air - where an initial absolute humidity of approximately 0.0005 is required to reduce condensation effects to negligible proportions.

2) Increasing stagnation temperature - a stagnation temperature greater than 400°F to eliminate condensation for Mach number of the order of 2.5.

Both of these methods require expensive installations and the second presents many difficulties in running technique.

A third method has been suggested by Royle[5] in which an auxiliary nozzle upstream of the test nozzle is used to

---

[4] J. K. Royle, "Control of Condensation Phenomena in Supersonic Tunnels by Pre-Expansion," Royal Aircraft Establishment Technical Note No. 1982 S. D. 69, February, 1948, p. 1.

[5] Loc. cit.

induce premature condensation. This type of system takes advantage of the fact that two types of condensation may occur. First, a comparatively slow type of condensation in the presence of atmospheric nuclei where the degree of supersaturation is small; and second, condensation occurring during rapid expansion where the degree of supersaturation is large. Now, if condensation of the slow type is induced upstream of the supersonic nozzle, the degree of supersaturation which occurs due to the rapid expansion at the supersonic nozzle will be reduced, and depending upon the amount of reduction, the condensation shock may be eliminated. Since the Relative Humidity of the air which is supplied to the tunnel is constantly changing in successive runs, it has been found advantageous to use an auxiliary nozzle with varying throat area. It will be noted that the condensation which has been induced in the auxiliary nozzle has not been disposed of, but passes through the test nozzle suspended in the air as fine droplets, ice particles, or possibly a mixture of these elements.

In the design of the supersonic nozzle, the method of characteristics was utilized as outlined by Puckett[6] in

---

[6] A. E. Puckett, "Supersonic Nozzle Design," Journal of Applied Mechanics, 13:A-265-70, December, 1948.

1946, and Shapiro and Edelman[7] in 1947, Figures 3,4, and 5. The basic steps incorporated in this method are:

1) Determine the Prandtl-Meyer expansion angle closest to the desired Mach number.

2) The maximum expansion angle $\theta_{MAX} = \nu/2$, choose $\theta_0 \leqq \theta_{MAX}$.

3) Choose an expansion curve from $0 - \theta_0$ and divide into $d\theta$ segments.

4) Construct the expansion waves and intersections, (flow net).

It will be noted that in (2) above θ_0 can be chosen $\leqq \theta_{MAX}$ if it $< \theta_{MAX}$, then the waves will reflect more than once and the nozzle will be of the longer type. In this design θ_0 was taken equal to θ_{MAX}, since that will give the shortest possible nozzle, and it has been pointed out by Bonney[8] that, while a longer nozzle will obtain better static pressure distribution, a short nozzle will allow less time for condensation to occur, and here the attempt is being made to eliminate condensation effects.

---

[7] A. H. Shapiro and G. M. Edelman, "Method of Characteristics for Two-Dimensional Supersonic Flow Graphical and Numerical Proceedings," Journal of Applied Mechanics, 69: A154, July, 1947.

[8] E. A. Bonney, Engineering Supersonic Aerodynamics (New York: McGraw-Hill Book Company, Inc., 1950), p. 47.

The Mach number designed for was 2.05 for which $\nu = 28^\circ$ this gave $\theta_{MAX} = 14^\circ$ and, in this case $\theta_{MAX} = \theta_0$ $d\theta$ was taken $= 2^\circ$ steps. For the required area at the minimum test section, it was assumed that a four inch deep test section was desired and the adiabatic area ratio equation[9]:

$$\frac{A_1}{A_*} = \frac{M_*}{M_1}\left[\frac{1 + \frac{\gamma-1}{2} M_*^2}{1 + \frac{\gamma-1}{2} M_1^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

was used and gave a minimum section 2.254 inches deep. The computations and characteristic angles needed are given in Figure 3. The shortest possible nozzle was obtained by first expanding θ_{MAX} degrees at the minimum section and finding the resultant flow net. This is shown in Figure 4. A nozzle could be designed like this, but any slight error in the contour would not allow the expansion to cancel properly. Therefore, a nozzle was designed by fairing a curve up to θ_{MAX} degrees and finding its resultant flow net, this is shown in Figure 5. It will be noted that this nozzle is slightly more than an inch longer than the shortest possible nozzle. It, therefore, could have the desirable effects of a short nozzle while not possessing the

---

[9] Ibid., p. 40.

sudden initial turn required in the shortest nozzle.

For boundary layer correction Puckett[10] states:

> "The rate of increase through a square section is such that an expansion of the top and bottom walls by 0.007 to .010 in./in. of length on each wall will roughly provide compensation for all four walls. This figure has been found to be useful for a wide range of R_e from $R_e = 5 \times 10^5$ to $R_e = 5 \times 10^6$ based on test section height and for Mach number of the order of 1.5 to 2.5."

This correction was arrived at through theoretical estimates of the rate of boundary layer growth and compared with boundary layer profiles measured in the Guggenheim Aeronautical Laboratories, California Institute of Technology, 2.5 inch supersonic tunnel. For this design the R_e was 3.06×10^6 and the Mach number was 2.05, but the maximum of .010 in./in. of length on each tunnel wall was used since a previous design by Thomas[11] indicated these values were conservative.

In the design of the humidity section, it was assumed that the two-dimensional channel depth was such that it would give a minimum speed of 370 feet per second after expansion by the auxiliary throat. Then, by assuming reservoir conditions of 60 psi and stagnation temperature

---

[10] Puckett, *op. cit.*, p. 3.

[11] G. B. Thomas, "Application of Water-Channel Compressible Gas Analogies to a Problem of Supersonic Wind Tunnel Design," (Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, 1949), p. 27.

of 520°R, it was possible by the basic flow equations to determine a channel depth of 3.88 inches. This particular minimum speed was used by Royle.[12] It was used in this experiment in order to draw a comparison with the data obtained from the work of Royle. The auxiliary nozzle was designed to be varied by the insertion of symmetrical airfoils of different thicknesses in the middle of the channel. The minimum section of the auxiliary nozzle was approximately 30 inches upstream from the throat of the supersonic nozzle.

---

[12] Royle, *op. cit.*, p. 3.

EQUIPMENT

The equipment used for this investigation was a two-dimensional supersonic tunnel of the blow-down type and a two-dimensional precondensation section.

Pressure System: The air was supplied by a "Worthington" ten horsepower compressor which operated at pressures up to 125 psig. This was connected to the pressure storage tanks by approximately 150 feet of one inch pipe. This considerable length of pipe gave a head loss of approximately 13 psi, but gave the advantage of allowing the air to cool before reaching the storage tanks.

The reservoir consisted of two tanks, one a small 4.2 cubic foot tank and the other a 176 cubic foot tank. Before entering the small tank, the air was passed through a porous stone filter installed in the line to remove any oil which was introduced and carried from the compressor The small tank was also utilized as a settling tank for any moisture which might have condensed in the cooling process carried out in the line. A safety valve was incorporated between the two tanks and adjusted to approximately 115 psig. This gave a positive margin of safety for the safe tested pressures (125 psig) for the two tanks.

The large tank was then connected to the pressure regulator by approximately fifteen feet of four inch pipe.

The Pressure Regulator and Valve: A high-pressure balanced regulator with a four inch line capacity was utilized. It also incorporated an additional regulator which controlled the balancing pressure across the diaphragm of the main regulator. The regulator could be set for a static pressure from 10 to 100 psig with an accuracy of $\pm$ 5 psig.

A quick-opening gate valve of four inch line capacity was used so that full utilization of the stored air could immediately be obtained. This, also, gave the advantage of cutting off the reservoir as soon as run measurements were taken, thus saving the air remaining in the tanks for the next run.

Transition Section: Following the quick-opening gate valve, a transition section cast out of aluminum was installed to geometrically converge the four inch circular, or three-dimensional flow, to a two-dimensional rectangular flow four inches deep and two inches wide. The convergence occurred over a length of nine inches and was considered slow enough not to introduce excessive turbulence into the channel flow.

The Precondensation Section: The precondensation section immediately followed the transition section and consisted of a variable throat and a rectangular channel 38 inches long. The throat of the auxiliary nozzle consisted of a spanwise symmetrical airfoil inserted into the center of the two-dimensional flow of the rectangular channel. Details of this installation are shown in Figures 2 and 6. By inserting airfoils of different thicknesses, it was possible to vary the minimum area of the throat. The three airfoils used were an NACA 66-008, and NACA 66-015, and an NACA 66-021, which were placed so that the maximum thickness point occurred at approximately the same position, thus giving the minimum section of the variable throat 30 inches ahead of the minimum section of the test nozzle. Thus, three different values of pre-expansion were made available.

The rectangular channel was constructed with plexiglass sides to facilitate flow observation and had mahogany blocks inserted for the top and bottom. The construction was such that the top could easily be removed. This greatly facilitated the interchanging of the different thickness airfoils.

Supersonic Nozzle: Immediately downstream of the precondensation section was the contraction for the supersonic wind tunnel. As will be noted in Figure 6 the contraction had a very short length in order to reduce boundary layer growth. The contraction reduced a 3.88 inch x 2 inch two-dimensional section to a 2.25 inch x 2 inch section in a distance of 1 3/8 inches.

Extending from the minimum section was the supersonic nozzle, which was designed by the method of characteristics as described on page 6 of the introduction and shown in Figure 5. The nozzle was designed to give a Mach number of 2.05 and possessed a test section four inches long, two inches wide, and four inches deep. To the depth dimensions boundary layer corrections were added as explained on page 9 of the introduction. At the end of the test section the air was expelled to the atmosphere.

The Schlieren System: For observing the flow in the plexiglass test section, a schlieren system was used. The source of light used for the system was a 400 watt BHL mercury vapor lamp receiving its power from an autotransformer with a rated open secondary voltage of 270 volts. This lamp produced a line of light measuring approximately 1/4 inch in width and five inches in length. It was mounted horizontally in the middle of an aluminum box ten inches square and eighteen inches in length. A parabolic mirror was mounted behind the lamp to converge the rays into a narrow slit. The box was mounted on an adjustable stand in order to permit the proper alignment of the light and slit to the optical axis of the system.

The light then passed through two condensing lenses narrowing the original beam down to a width of 1/16 inch x 1.625 inches in length. A narrow slit 1 1/2 inches long was introduced at this stage to cut out all light except the most intense light in the middle. The slit was located at the focal point on a war surplus Kohad Aero Ektar, 13.5 inch f/3.5 camera lens. Light passing through the slit expanded to cover and pass through the lens. At one focal length, the test section was perpendicular to the optical axis. The rays of light then passed through the section and continued to a lens like the one described before, but in the opposite direction. The lens was located two focal lengths behind the test section since it was discovered to be the minimum distance producing a clear picture of the test section. The lens made the rays converge once more so that at one focal length on the other side of the lens the light converged into a line equal to the original slit. A knife edge was then introduced to cut out the bottom half of the light line. Then the other half continued to a "Graflex" camera mounted where a clear picture might be obtained with the lens removed. The camera used cut film and the lens was removed in order to let the light shine directly on the film.

In order that the system could be moved to view any point along the tunnel, the whole system, light, lenses, etc., were placed on a channel iron base, which in turn was mounted on adjustable ways.

Instrumentation: A pressure gage, accurate to 1/2 psig, was installed in the line between the regulator and quick-opening gate valve. Since the velocity in the line was so great, this was only an indicator of the static pressure by the time the flow had stabilized. A vapor pressure, bulb-type thermometer, accurate to $1/2^{\circ}$ Centigrade, was installed near the pressure gage.

In order to obtain the proper values of Relative Humidity, a standard sling-type psychrometer was utilized at the source of air before it proceeded through the compressor. This was coupled with barometric pressure readings taken at the same point.

Pitot tubes were installed at the entrance to the precondensation section and the entrance to the supersonic nozzle. These were used to indicate the total pressure entering both positions so that the loss through the precondensation section could be found.

Static pressure orifices were installed in the following stations:

1) Precondensation Section
   a. entrance
   b. four inch intervals from entrance
   c. exit

2) Supersonic Nozzle

   a. minimum section

   b. two inches downstream of throat

   c. 4 inches downstream of throat

   d. 6 inches downstream of throat

   e. 8 inches downstream of throat

   f. 10 inches downstream of throat

Their installation may be observed in Figure 2.

A multiple bank of mercury manometer tubes were used to indicate the pressures and the readings were recorded photographically.

The cameras taking the pictures for the schlieren and manometer banks were fired by solenoids which were synchronized to take pictures when the static pressure from the throat reached a certain height, or by switches located at the schlieren and the quick-opening gate valve. This arrangement allowed a variety of ways in which pictures could be taken.

A 20° wedge which completely spanned the tunnel, was installed at the center line of the tunnel in order to induce oblique shock waves. The wedge was fastened to the tunnel side by two holding pins. This is shown in Figure 1.

PROCEDURE

A set of preliminary runs were first made in order to check the length of runs, manometer connections, cameras, and solenoids during a run. These runs were made and the pictures taken were analyzed to get an idea of what to expect and prepare for in the following test runs.

The test runs were taken in three series of twelve, each made on different days, in order to get a comparison of the effects of different Relative Humidity. A series of twelve runs consisted of three each for each of the three airfoils used in the precondensation section, one showing the shock waves off of the wedge, one giving the normal condensation shock (if it existed), and one observing the flow on the trailing edge of the airfoil in the precondensation chamber. Finally, three runs were made utilizing the supersonic nozzle without the precondensation section, one run showing the shock off of the wedge, another showing the condensation shock, and the third showing the normal type condensation shock as it approached the throat.

To supplement this data, a series of ten runs were made during which pitot static readings were taken of the flow as it entered and left the precondensation section.

The following procedure was used to obtain data from the supersonic wind tunnel: First, the mercury vapor lamp was turned on and allowed to warm for approximately twenty minutes. At the same time, the valves were opened from the compressor line to allow the tanks to fill up with air. This required thirty minutes if the tanks were at zero gage pressure.

When the light had warmed sufficiently, the cameras were focussed and set at the proper speed. Then, as soon as the tanks reached the required pressure, the gate valve was opened; and then allowing one second for the flow to develop, the camera of the schlieren system was tripped, along with the camera photographing the manometer bank.

RESULTS AND ANALYSIS

During the preliminary runs, the pictures obtained from the schlieren had alternate vertical streaks of dark and light, which had not been visible to the naked eye while observing flow through the schlieren, Figures 7, 8, 9, 10 and 11. Since it was desired to eliminate these streaks, an investigation was made to determine their origin. It was first suspected that extraneous light was coming into the system; therefore, runs were made at night with no lights overhead, and the streaks still remained. Next, to eliminate the possibility of the camera or film being at fault, pictures were taken with the camera shifted from a horizontal to a vertical position. Positive results were obtained here because the lines shifted from vertical to horizontal. This seemed to indicate that either the camera or film was at fault. It was known that the film was all right since part of the same emulsion batch was being used for other projects; therefore, a different camera of the same type was tried and the results were similar to those previously obtained. Apparently the light source in the schlieren was at fault. The "Graflex" camera, which held the film, was operated without a lens; the focal plane shutter of the camera was used to expose the film. A "Speed Graphic" camera was then tried utilizing the front shutter. The vertical streaks were eliminated by this method. Hence, the streaks were traced to the mercury vapor source pulsing on and off. However, the remainder of the test pictures were taken using the focal plane shutter since it gave the necessary data needed for these pictures. Installing a "Speed Graphic" would have involved difficulty in focussing and no means would be provided for observing the flow up until the time when the pictures were to be taken.

The wind tunnel was designed for a Mach number of 2.05. This particular value was used since it was desired to obtain a Mach number in the vicinity of two and the Prandtl-Meyer expansion angle for Mach number 2.05 particularly simplified the design. In analyzing the angles obtained from the 20° wedge it was noted that for condensation free flow an angle of 38° was obtained from the lower shock. This apparent difference could have occurred due to a part or combination of two causes. First, the wedge might not have been symmetrical to the flow, in which case a solution may be obtained by solving for a common Mach number using various combinations of wedge half angles and oblique shock angles that combine to give a 20° wedge angle and a 77° oblique shock angle. This was done and the solution indicates that the Mach number was 2.04 and the wedge was inclined 1/2° to the flow. A second cause could have been that the reference center line on the tunnel wall was off 1/2°, in which case the oblique shock angle should have been 38.5° which indicates a Mach number of 2.045. Both of these solutions give values within 1/2 per cent of the Mach number designed for.

In a previous experiment conducted by Head,[13] two main types of discontinuities were found to occur, the condensation shock and the shock with condensation (or vaporization). Certainly the first is by far the most critical, but as is shown in the curve of Figure 14, the variation of Mach number for shocks with condensation if neglected could result in considerable error. However, in the tests conducted for this project it was found that the variation of the Mach number was not critical. In fact no variation could be observed while, as will be noted from Figure 14 for the nozzle used in these tests, there should be a change of 2.5 per cent.

During the preliminary runs it was found that the precondensation section was inducing condensation as it was designed to do. Further, the different auxiliary throat area settings seemed to have considerable influence on the amount of visible condensation that was induced. As the test runs continued on successive days following the preliminary runs it became apparent that at times when the

---

[13] Richard M. Head, "Investigations of Spontaneous Condensation Phenomena," (Unpublished Ph. D. Thesis, California Institute of Technology, Pasadena, 1949), p. 12.

stagnation Relative Humidity dropped to a value of 63 per cent or below that it would not be desirable to use the precondensation section. This was true since neither a condensation shock or shock with condensation occurred in the nozzle alone, while with the use of the precondensation section a shock with condensation was always produced. No oblique condensation shocks occurred with or without the use of the precondensation section and normal condensation shocks were observed to occur only as the tunnel blew down at the end of the run.

It is felt that while Royle[14] experienced icing conditions in his experiments, that this would not often occur in the short duration of the blow-down type of tunnel used in these tests, since the pressure was continually varying and the average run time was of the order of five seconds. Probably a stable condition for icing and mist conditions did not always exist for a long enough period to be observed. On one very moist day when the humidity was 81 per cent a deposit of ice particles was left on the test section walls and ice particles were observed in the flow. It should be emphasized that this was not a film of ice, such as Royle found, but a deposit of ice particles. The blow-down type of tunnel would,

---

[14] Royle, op. cit., p. 5.

therefore, seem to possess an advantage in that the conditions for icing and mist do not often occur.

The simplest and most logical method for accurately determining the location and intensity of the collapse of the supersaturated state in a wind tunnel is by means of static pressure measurements. This is due to the fact that a sudden release of heat, resulting from the spontaneous condensation, causes the flow parameters to deviate from their isentropic values at that point. Hence, for given stagnation conditions, the location of the collapse is obtained from static pressure distribution measurements as that point at which the ratio p_i/p_* starts diverging from the corresponding isentropic curve.

An attempt was made to use this method during the course of these experiments. However, due to the short duration of the runs (approximately five seconds), and the fact that a constant pressure was held by the regulator for only one second, it was not possible to obtain a complete set of pressure readings from any one run. Therefore, a statistical check was made of the total aggregate of runs to obtain the most probable values of the pressure ratio distribution, Figure 12.

In order to analyze the Relative Humidity of the air that was being supplied by the regulator, a set of curves were computed and drawn, Figure 13. The data needed was taken from a set of nomographs which were designed by Brooks[15] for high and low pressures. By the use of this chart it was possible to take sling psychrometer readings at the compressor and dry bulb temperatures of the air being supplied by the regulator and find the sea level equivalent Relative Humidity at 60 psig. The stagnation pressure was assumed to be 60 psig, since the pressure readings and manometer readings were taken after the regulator stabilized to this condition. It will be noted that the 90°F dry bulb temperature line lies below the 70° F line, while the 80°F line lies above the 70° F line. This is not hard to understand if they are visualized to all be lines of different temperature.

An interesting phenomena appeared during the runs in which oblique shocks with condensation occurred. This phenomena appears in Figures 7 and 8; it occurred during the runs after the stabilized pressure interval as the pressure dropped below a stagnation pressure of 60 psig and it proceeded as the successive pictures show. First, apparent flow lines appeared to start flowing up the oblique shock; then, for a brief instant after maximum flow was established, small vortices were formed which had larger radii relative to their position out on the oblique

---

[15] B. B. Brooks, "Psychrometric Charts for High and Low Pressures," National Bureau of Standards Miscellaneous Publication No. M146, December, 1935, p. 6.

shock wave. Finally, the phenomena disappeared entirely and a faint oblique shock could be observed as shown in Figure 8a, then the normal shock travelling toward the throat due to the decrease in pressure, moved across the wedge, as will be noted in Figure 8b, and the oblique shock became fainter as the normal shock moved across.

The apparent flow lines were probably visible particles of moisture giving a trace of their trajectories. They would appear this way due to the slow shutter speed. How these particles were forewarned of the shock wave they were approaching, raises some very interesting questions.

It was also noted that, as the normal shock passed the tip of the wedge on its way to the throat, the oblique shock wave angle began to increase. This would seem to indicate that the normal shock was a normal condensation shock, since an increase in oblique wave angle indicates a decrease in Mach number and a condensation shock decreases a Mach number to some value above Mach one.

CONCLUSIONS

(1) The precondensation induced condensation and reduced the possible supersaturation due to the sudden expansion in the nozzle.

(2) Different area settings of the auxiliary nozzle in the precondensation section made a noticeable difference in the amount of condensation induced into the flow, a smaller area or greater expansion inducing more droplets.

(3) Since the necessary conditions for a condensation shock did not occur in the nozzle used for these tests, the precondensation section would not need to be used.

(4) The supersonic nozzle alone would seem to have an advantage for this nozzle, in that on days when the stagnation Relative Humidity is low oblique shock waves with no condensation effects may be obtained.

RECOMMENDATIONS

(1) Try a nozzle utilizing a precondensation section followed by a centrifugal separator. This could be used for drying air which could then be returned to the compressor and recompressed for use in the supersonic nozzle.

(2) A larger reservoir capacity should be provided whereby the time of a run could be lengthened to allow a sufficient period for the regulator to stabilize.

(3) The schlieren system should be provided with a camera which utilizes a front shutter. This could be supplemented by an auxiliary schlieren system which would be observed from the position at which the gate valve is opened and closed.

(4) In order to provide better flow visualization with the schlieren system, glass with the proper optical qualities should be used for the tunnel and test section walls.

(5) A nozzle of the longer type should be tried and a comparison made with the short nozzle as to the advantage or disadvantage in a longer nozzle of better boundary layer and flow properties relative to its poor condensation qualities.

Ferri, Antonio, "Investigations and Experiments in the Guidonia Supersonic Wind Tunnel." U. S. National Advisory Committee for Aeronautics Technical Memorandum No. 901, July, 1939.

Hawthorne, W. R., and H. Cohen, "Pressure Losses and Velocity Changes Due to Heat Release and Mixing in Frictionless Compressible Flow." Royal Aircraft Establishment Report No. E3997, January, 1947.

Head, Richard M., "Investigations of Spontaneous Condensation Phenomena." Ph. D. Thesis, California Institute of Technology, 1949.

Heybey, "Analytical Treatment of Normal Condensation Shocks." U. S. National Advisory Committee for Aeronautics Technical Memorandum No. 1174, 1947.

Hicks, Bruce L., "Addition of Heat to a Compressible Fluid in Motion." U. S. National Advisory Committee for Aeronautics Advanced Confidential Report No. E5A29, February, 1946.

_______, Donald J. Montgomery and Robert H. Wasserman, "The One-Dimensional Theory of Steady Compressible Fluid Flow in Ducts with Friction and Heat Addition." U. S. National Advisory Committee for Aeronautics Technical Note No. 1336, July, 1947.

Kantrowitz, A., "The Formation and Stability of Normal Shock Waves in Channel Flows." U. S. National Advisory Committee for Aeronautics Technical Note No. 1225, March, 1947.

Liepmann, H. W., H. Askenas, and J. D. Cole, "Experiments in Transonic Flow." Air Force Technical Report No. 5667, Wright-Patterson Air Force Base, Dayton, Ohio, June, 1947.

Lukasiewicz, "Humidity Effects in Supersonic Flow of Air." Royal Aircraft Establishment Technical Note No. Aero 2211, July, 1947.

Pearcey, H. H., "The Effect of the Condensation of Atmospheric Water Vapor on Total Head and Other Measurements in the NPL High Speed Tunnels." British Aeronautical Research Committee Reports and Memoranda No. 2249, September, 1949.

Redington, "An Investigation of Condensation Phenomena in a Small Supersonic Nozzle." Cornell Aeronautical Laboratory Report No. AF-390-7, June, 1946.

Royle, J. K., "Control of Condensation in Supersonic Tunnels by Pre-Expansion." Royal Aircraft Establishment Technical Note No. 1982 S. D. 89, February, 1948.

Taylor, G. I., "The Flow of Air at High Speeds Past Curved Surfaces." British Aeronautical Research Committee Reports and Memoranda No. 1381, February, 1930.

Temple, G., "The Method of Characteristics in Supersonic Flow." British Aeronautical Research Committee Reports and Memoranda No. 2091, January, 1944.

Thomas, G. B., "Applications of Water-Channel Compressible Gas Analogies to a Problem of Supersonic Wind Tunnel Design." Masters Degree Thesis, Georgia Institute of Technology, September, 1949.

Tollmien, W., "Theory of Characteristics." U. S. National Advisory Committee for Aeronautics Technical Memorandum No. 1242, September, 1949.

(Periodicals)

Bailey, N. P., "The Thermodynamics of Air at High Velocities," Journal of Aeronautical Sciences, Vol. 2, 1944, p. 227.

Binnie, A. M., "The Pressure Distribution in a Convergent Divergent Steam Nozzle," Institution of Mechanical Engineers, Vol. 138, p. 229.

Chambre, P., and C. Lin, "On the Steady Flow of a Gas Through a Tube with Heat Exchange or Chemical Reaction," Journal of Aeronautical Sciences, Vol. 13, 1946, p. 537.

Keenan, J. H., and E. P. Neumann, "Measurement of Friction in a Pipe for Subsonic and Supersonic Flow of Air," Journal of Applied Mechanics, Vol. 13, 1946, p. A-91.

Oswatitsch, K., "Formation of Fog in Wind Tunnels and Its Effect on Model Tests," Luftfahrtforschung, Vol. 18, 1941.

Powell, C. F., "Condensation Phenomena at Different Temperatures," _Proceedings of the Royal Society of London_, Vol. 190, 1947, p. 137.

_______, "Supersaturation of Steam and Its Influence on Some Progress of Steam Engineering," _Engineering_, June 7, 21, 1929, Vol. 127.

Puckett, A. E., "Supersonic Nozzle Design," _Journal of Applied Mechanics_, Vol. 68, December, 1946, p. A265.

Rettaliata, J. T., "Undercooling in Steam Nozzles," _American Society of Mechanical Engineers Transactions_ Vol. 58, 1936, p. 599.

Samaras, D. G., "Gas Dynamic Treatment of Exothermic and Endothermic Discontinuities," _Canadian Journal of Research_, Vol. 26, 1948, p. 1.

Shapiro, A. H. and G. M. Edelman, "Method of Characteristics for Two-Dimensional Supersonic Flow Graphical and Numerical Procedures," _Journal of Applied Mechanics_, Vol. 69, July, 1947.

_______, and W. R. Hawthorne, "The Mechanics and Thermodynamics of Steady One-Dimensional Gas Flow," _Journal of Applied Mechanics_, Vol. 69, 1947, p. A317.

Tsien, H. S., "Wind Tunnel Testing Problems in Superaerodynamics," _Journal of Aeronautical Sciences_, Vol. 15, 1948, p. 573.

Yellot, J. I., "Condensation of Flowing Steam," _Engineering_, Vol. 143, 1937, p. 647.

_______, "Supersaturated Steam," _American Society of Mechanical Engineers Transactions_, Vol. 56, June, 1934, p. 411.

APPENDIX I

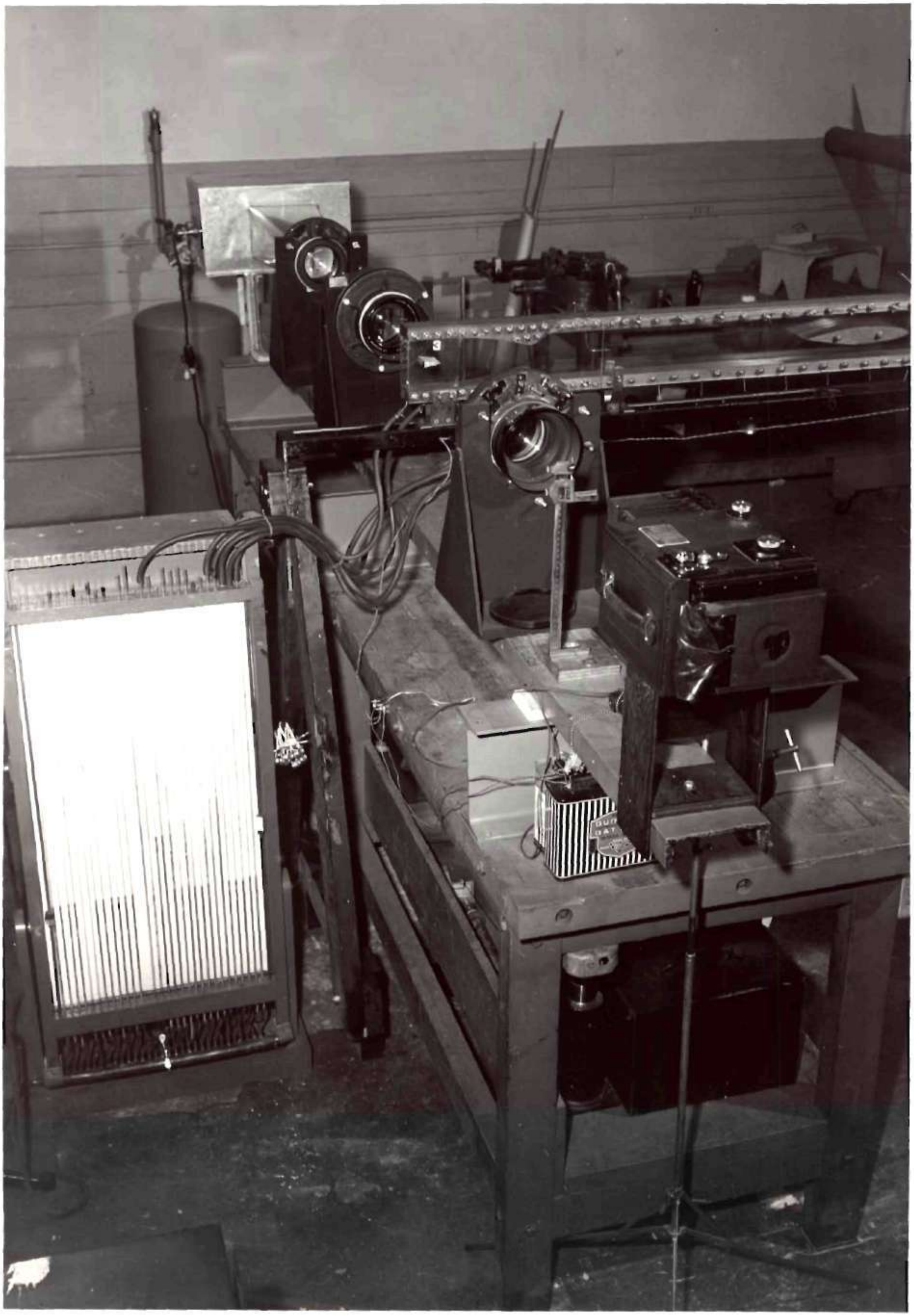


Figure 1. General View of Wind Tunnel

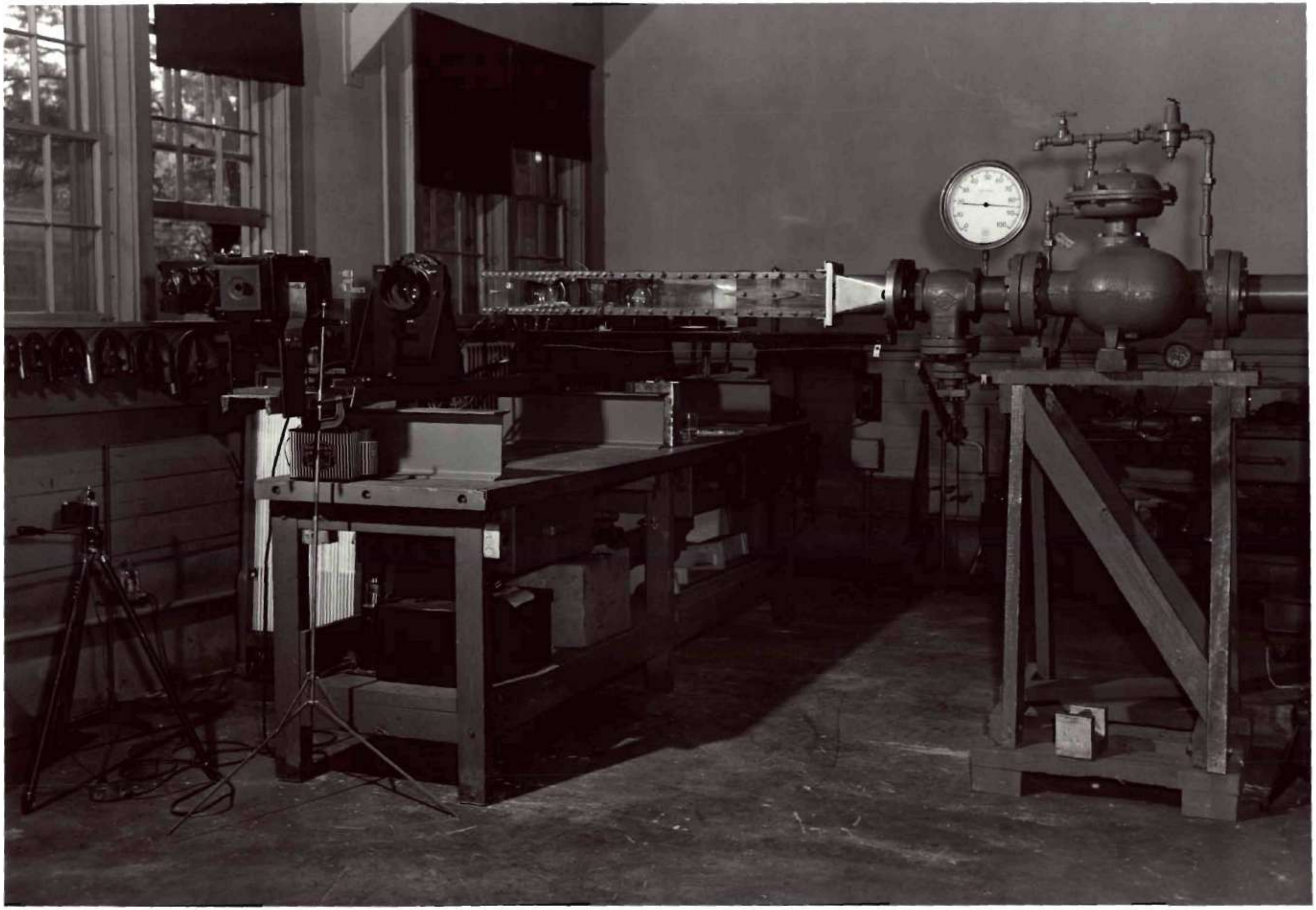


Figure 2. General View of Precondensation Section

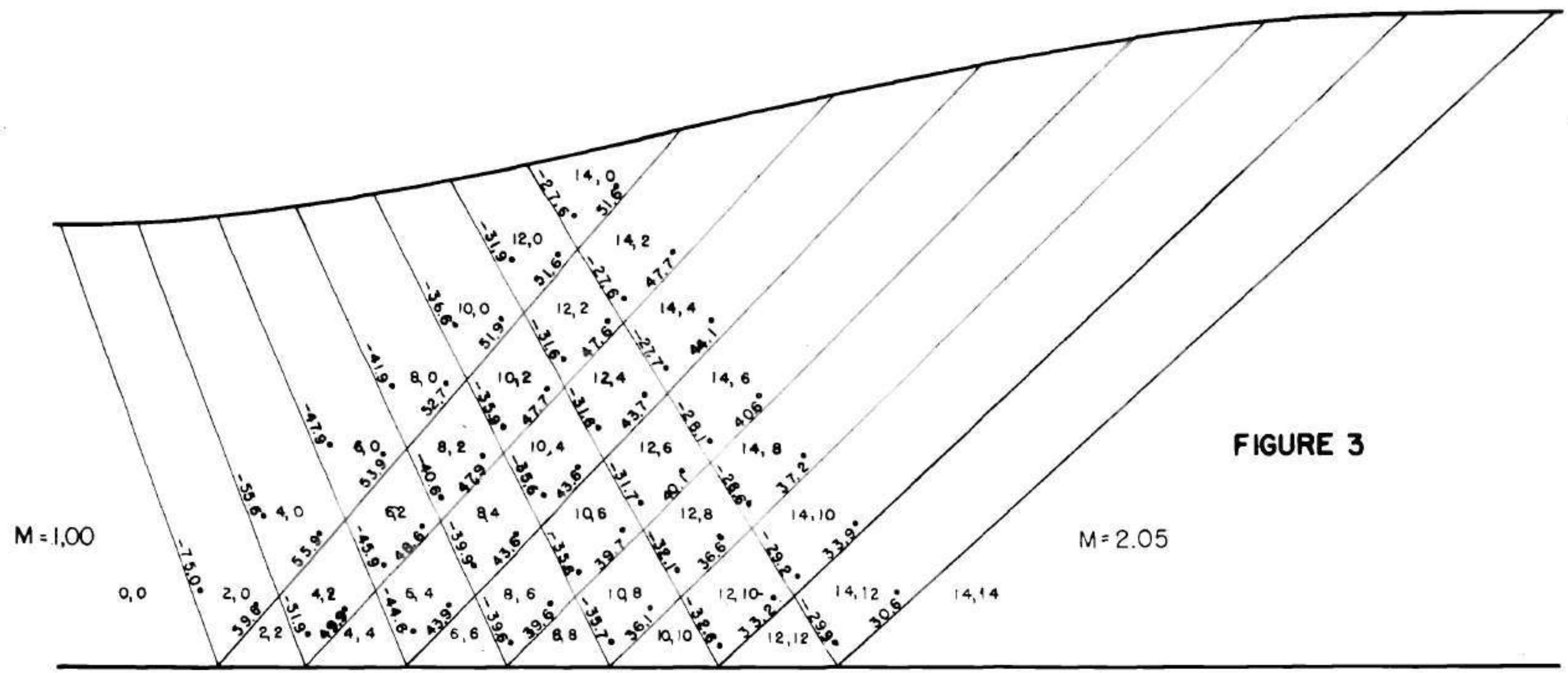


FIGURE 3

SUPERSONIC NOZZLE DESIGN

BY

THE METHOD OF CHARACTERISTICS

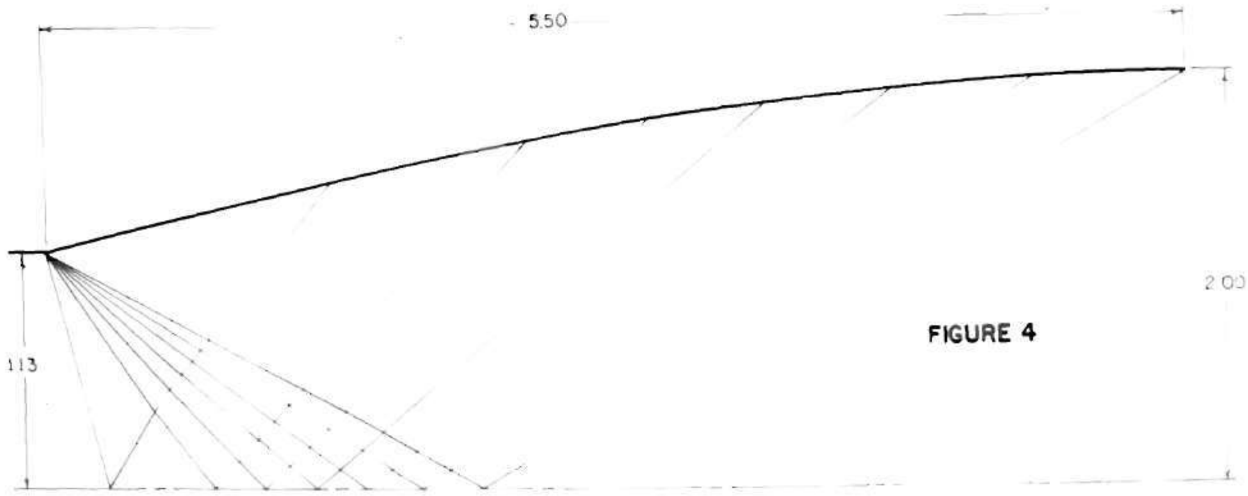


FIGURE 4

SHORTEST POSSIBLE NOZZLE

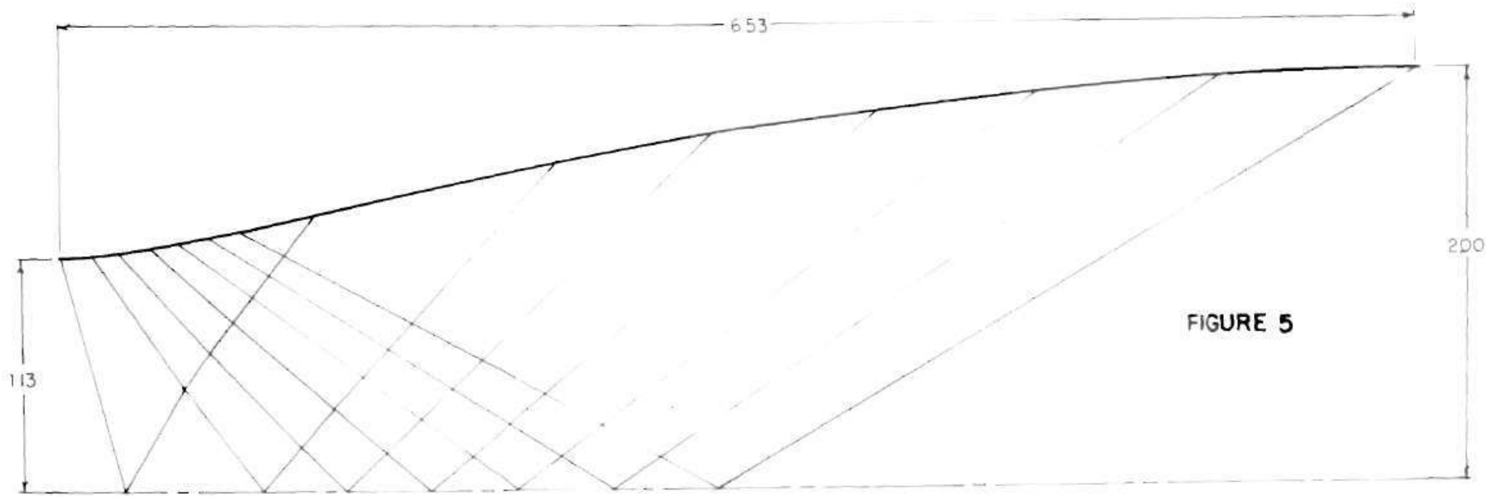


FIGURE 5

FINAL NOZZLE DESIGN

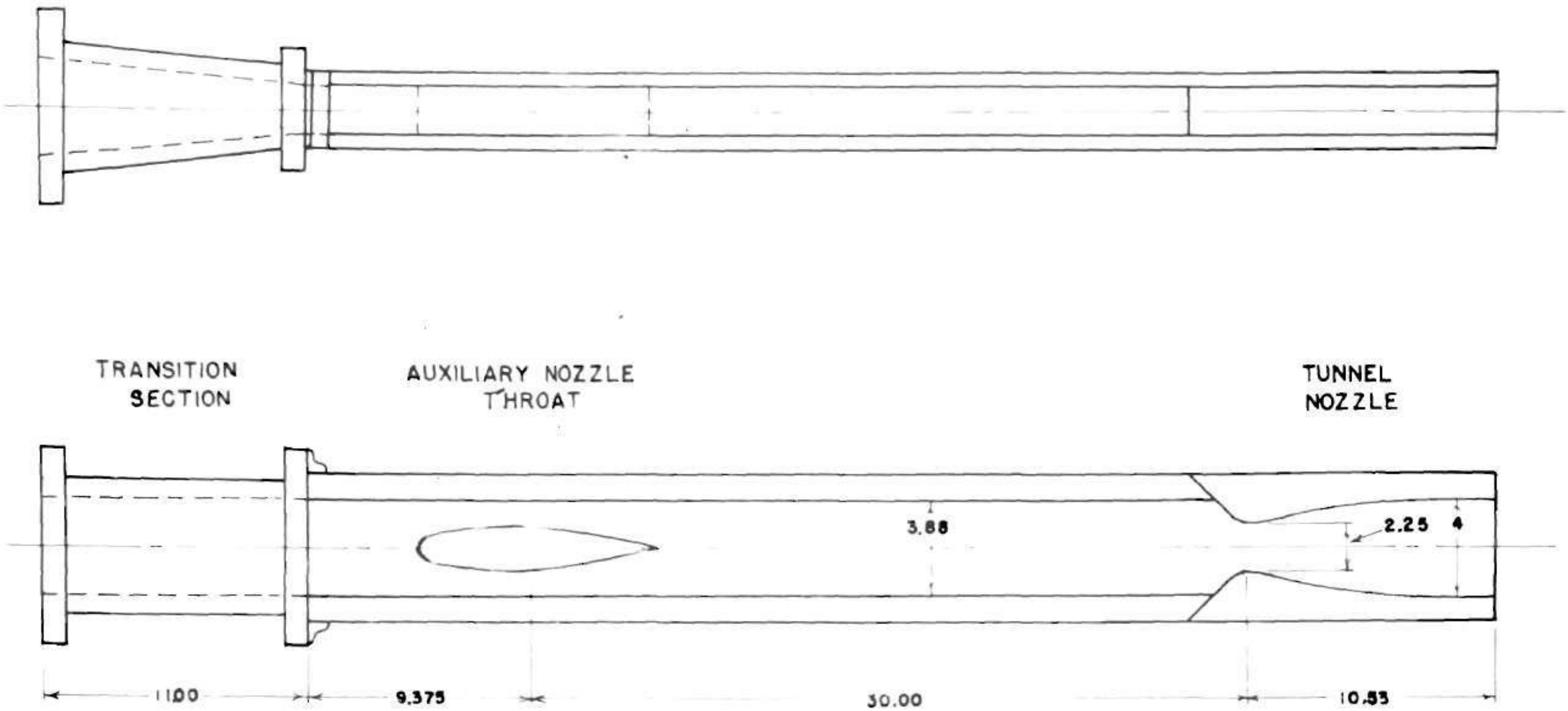
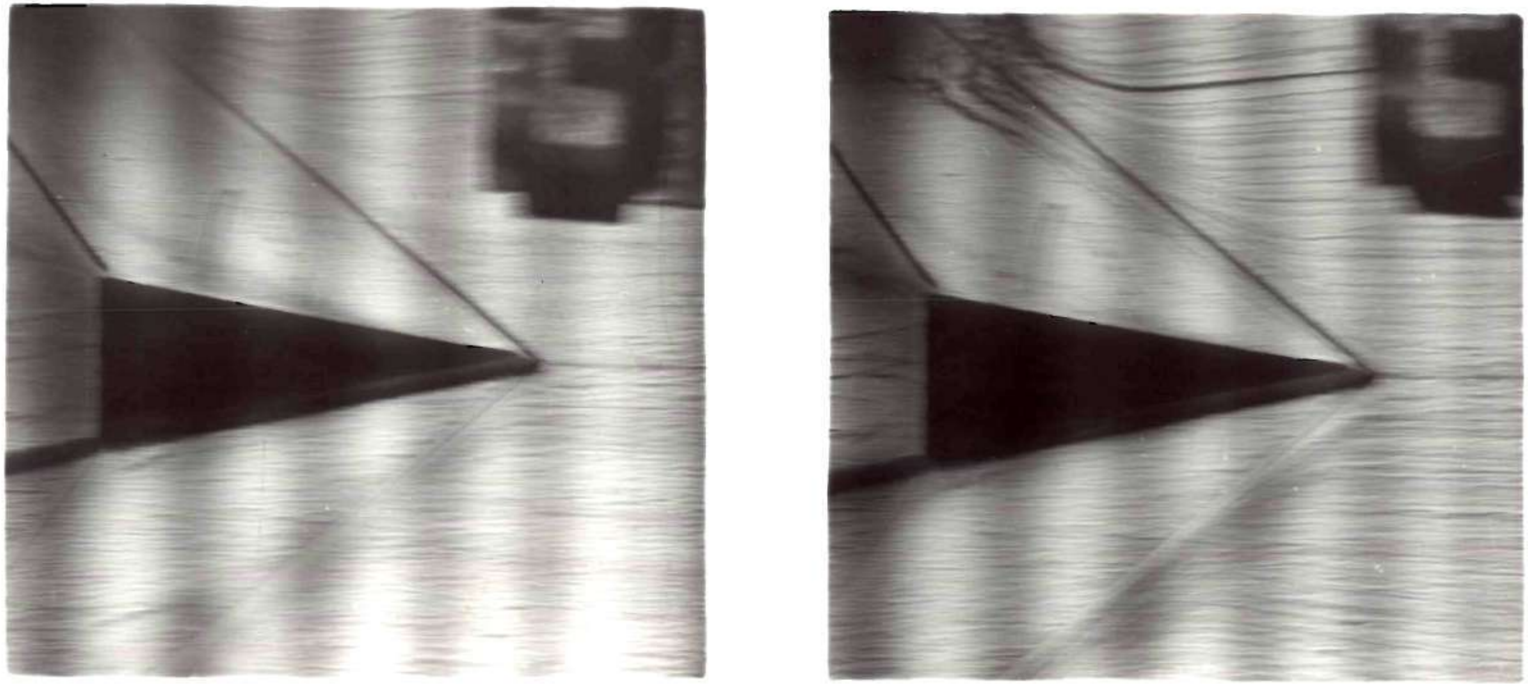
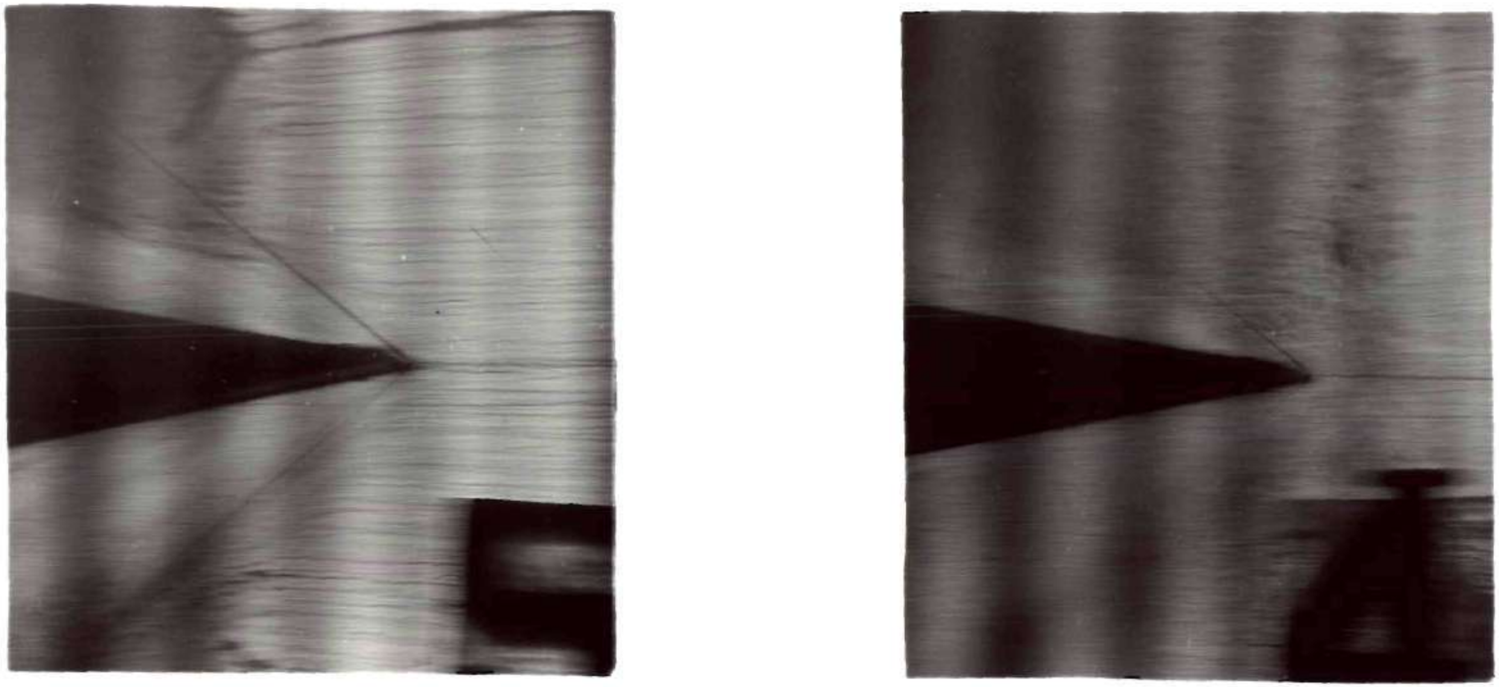


FIGURE 6 2×4 IN. SUPERSONIC TUNNEL WITH PRECONDENSATION SECTION



(a) (b)

Figure 7. Appearance of Strange Phenomena



(a) (b)

Figure 8. Disappearance of Strange Phenomena

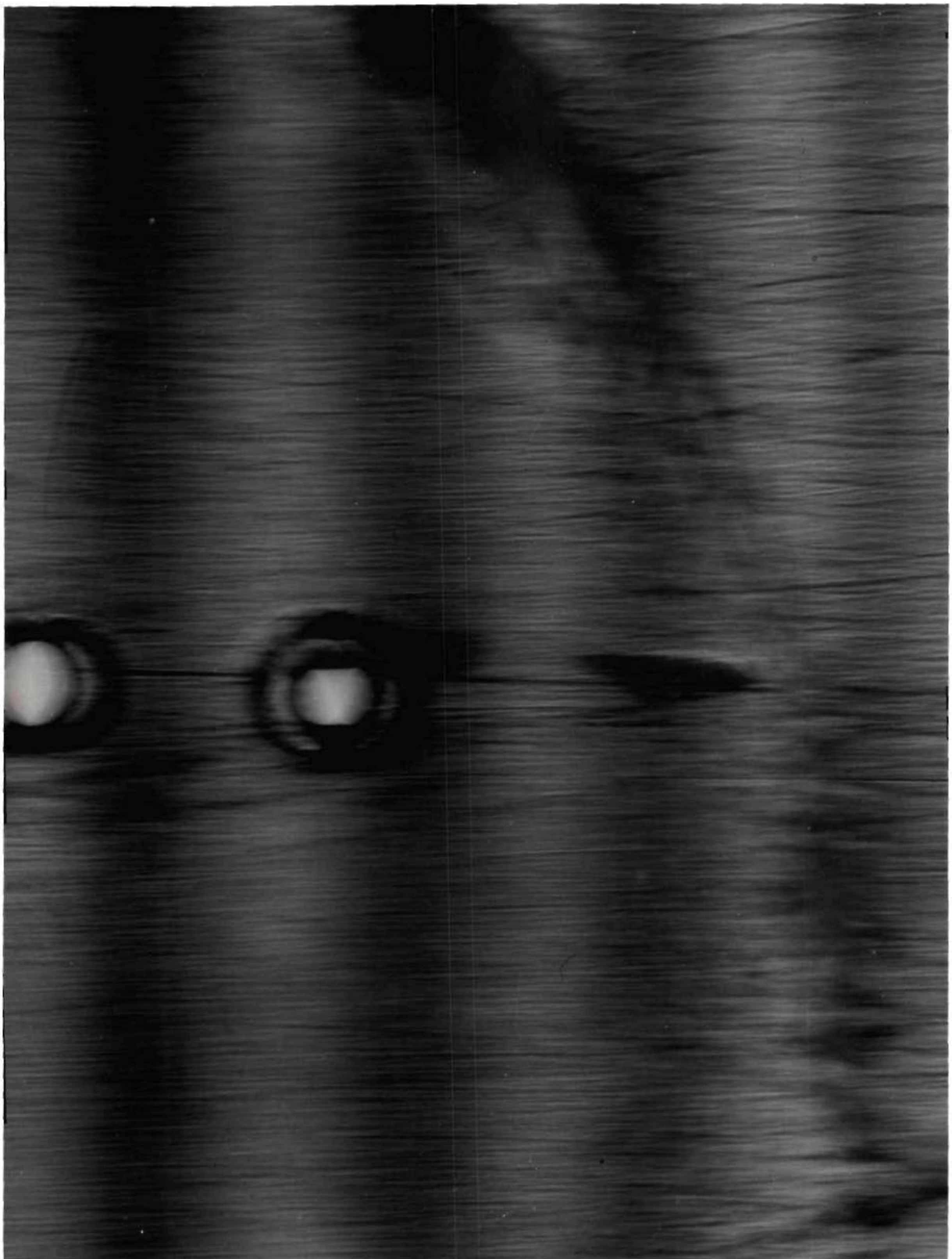


Figure 9. Normal Condensation Shock

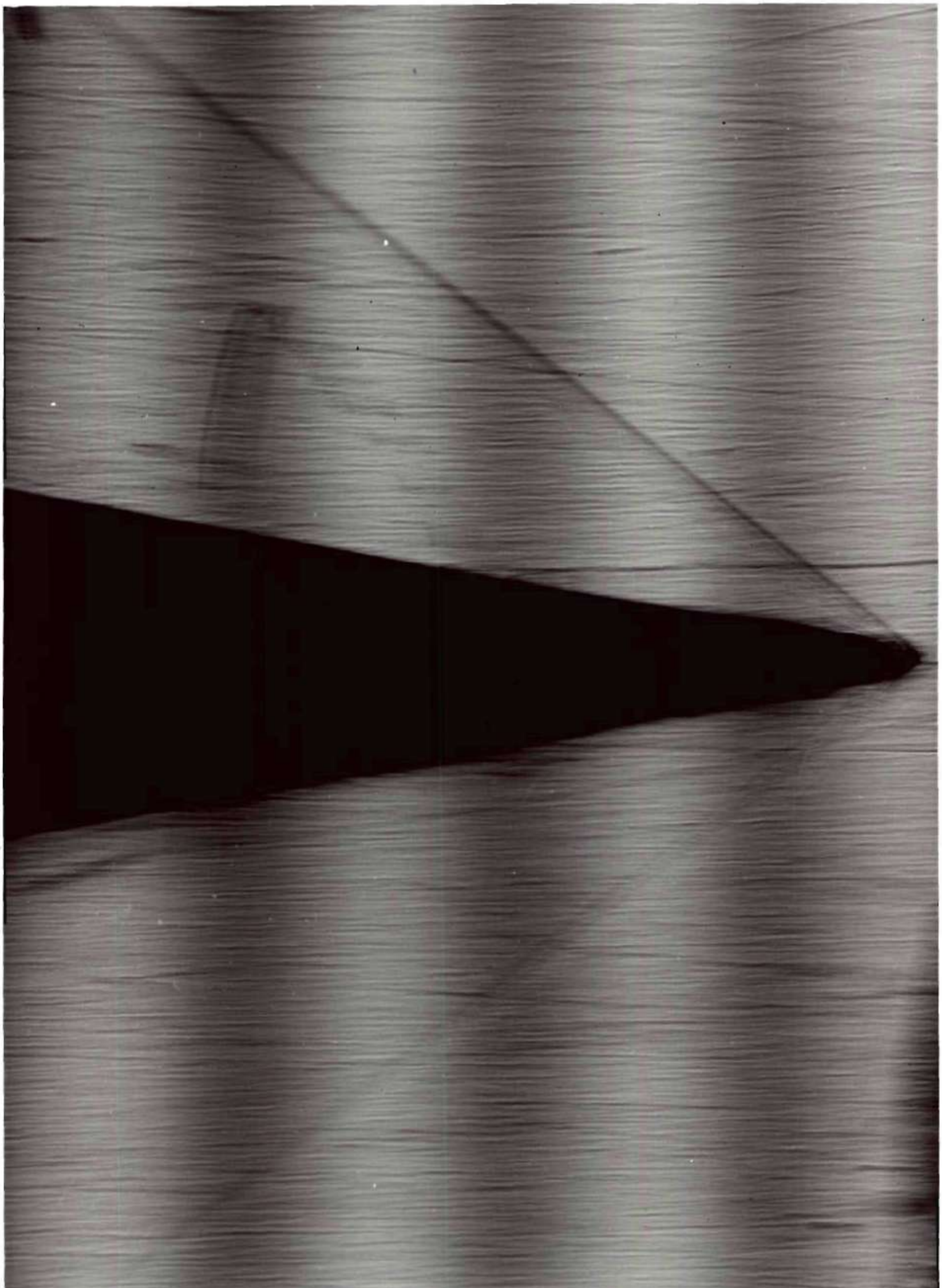


Figure 10. Oblique Shock with No Condensation

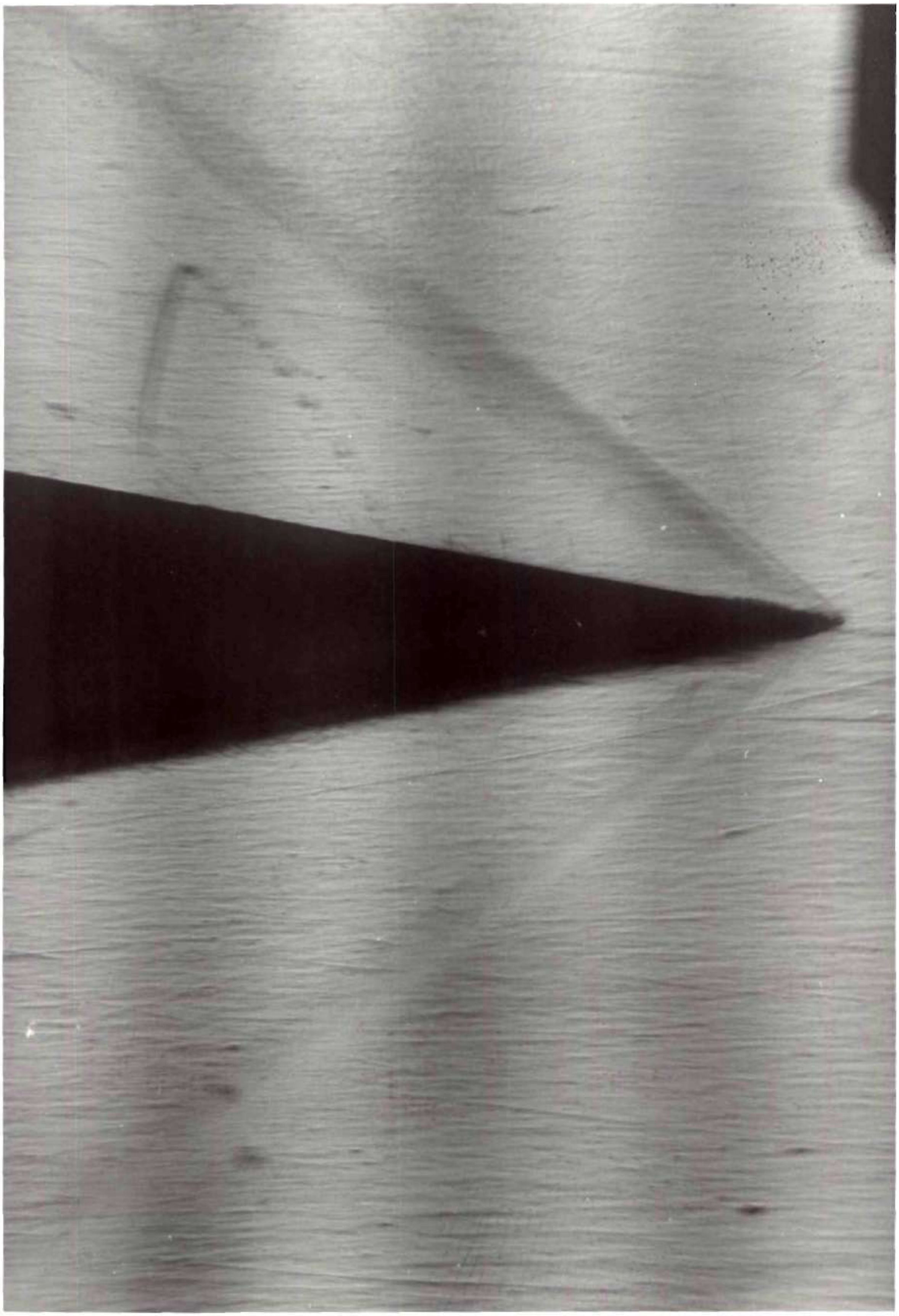


Figure 11. Oblique Shock with Condensation

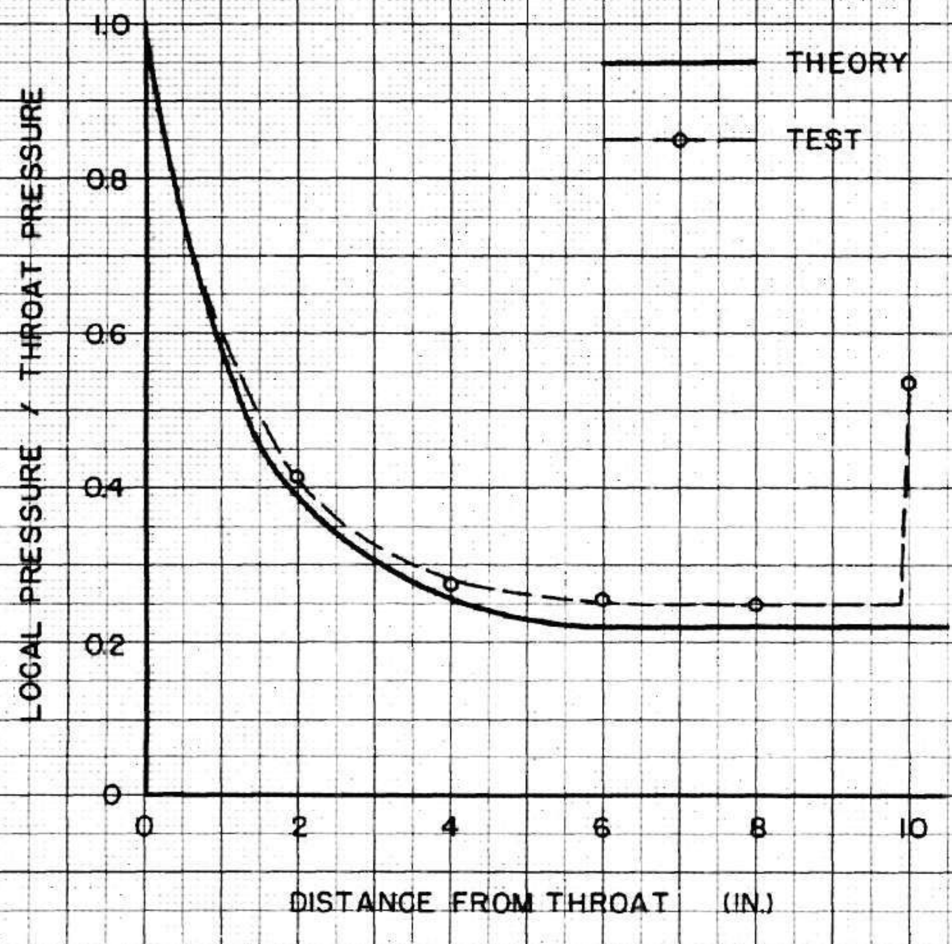


FIGURE 12 LAVAL NOZZLE PRESSURE DISTRIBUTION

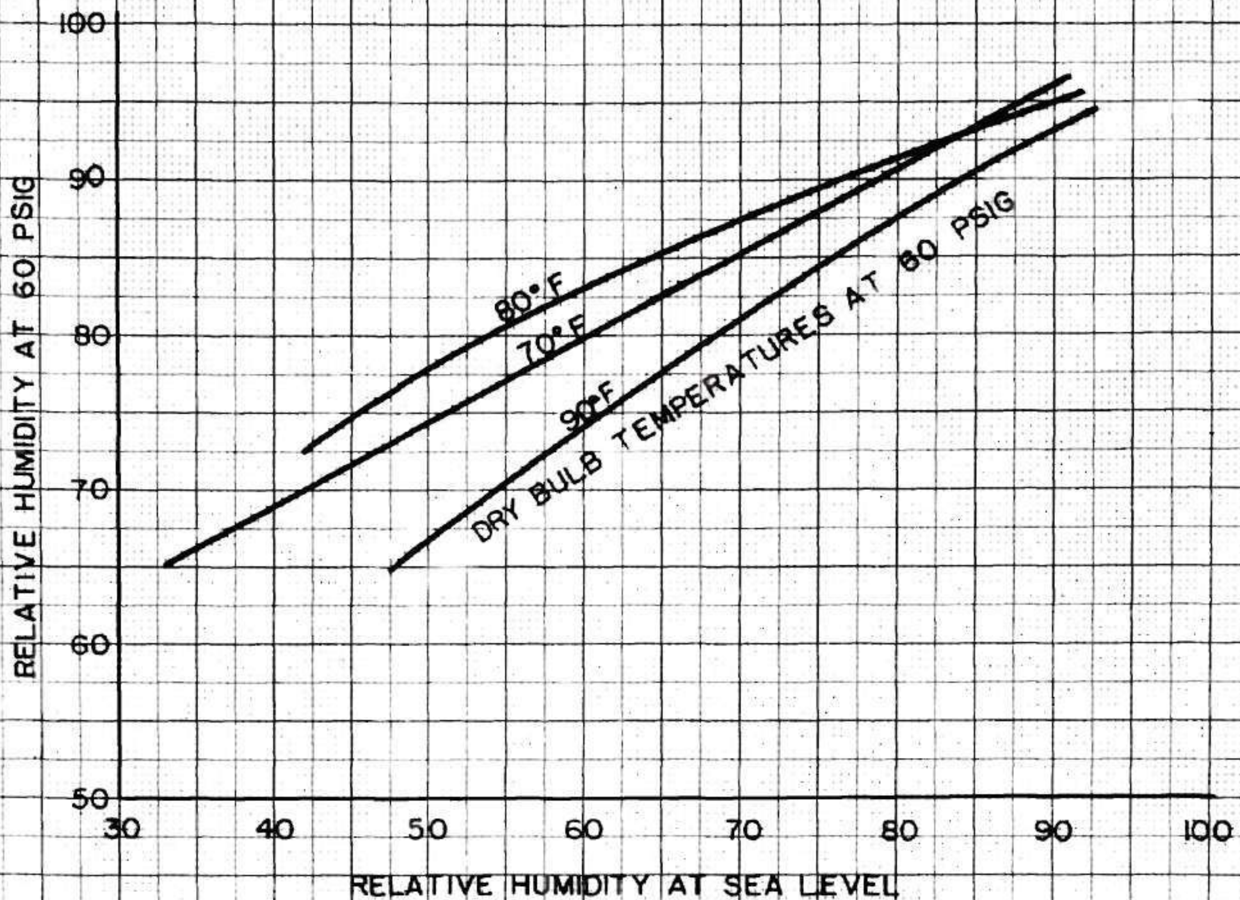


FIGURE 13 PSYCHROMETRIC CONVERSION CHART

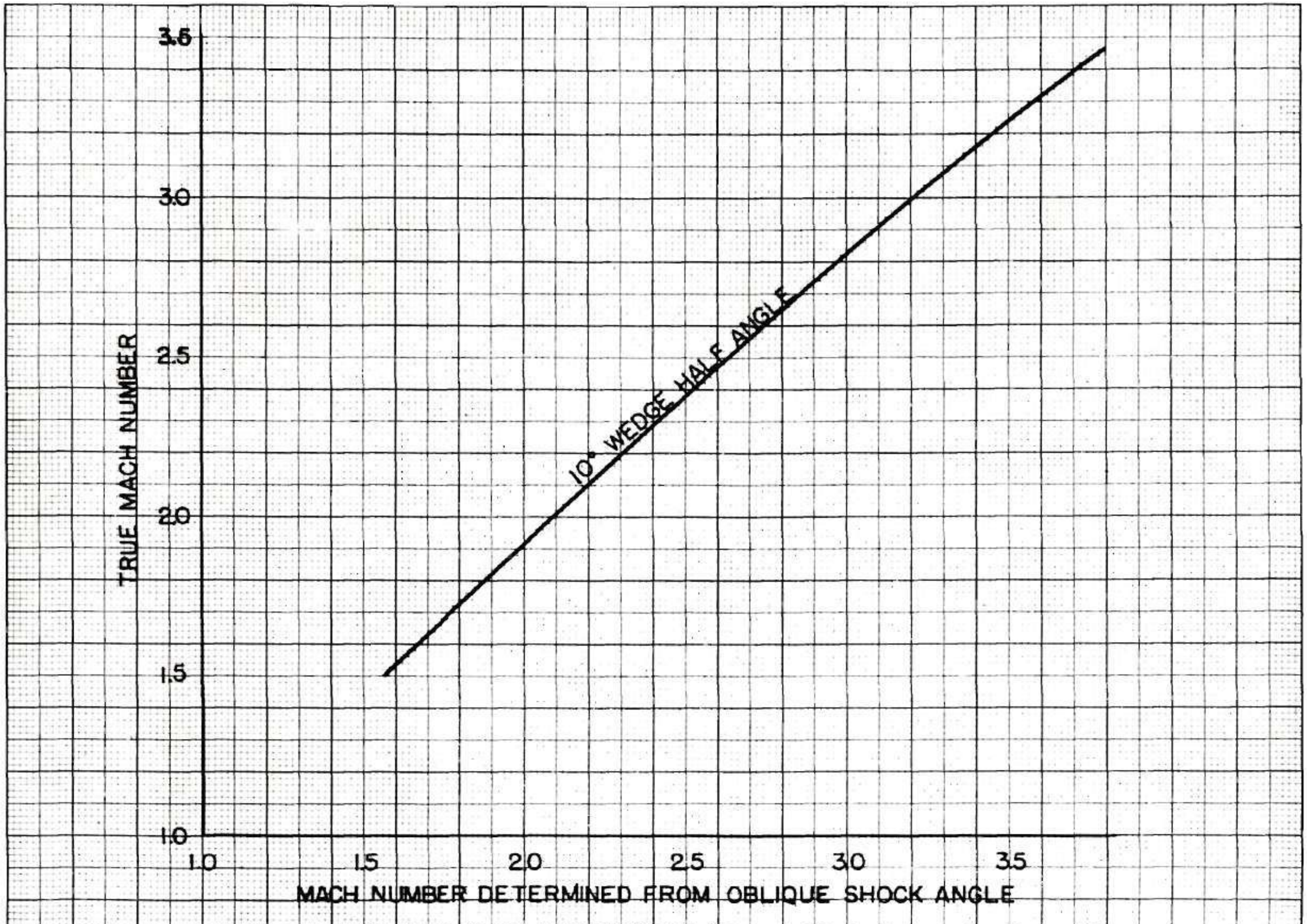


FIGURE 14 ERROR IN MACH NUMBER DUE TO VAPORIZATION OF DROPLETS

240464